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14. ABSTRACT

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Dark core analysis of coaxial injectors at sub-, near-, and supercritical conditions in a transverse acoustic field

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ABSTRACT

An experimental study on the effects of an externally-imposed transverse acoustic field in sub-, near-, and supercritical N2 coaxial jets is presented. Such fields and their interaction with the jets (i.e., breakup, mixing, etc.) is believed to play a critical role during combustion instabilities in liquid rocket engines. The shear coaxial injector used here is similar to those used in cryogenic liquid rockets. By using N2 as the working fluid, the chemistry effects on combsution instability are separated from the effects of a transverse acoustic field on coaxial jets. Furthermore, through this choice, ambiguities associated with compostion dependence on mixtures critical properties are eliminated. The acoustic oscillations are generated by a piezo-siren and have a frequency of ~3kHz. The pressures in the chamber range from 215-716 psia to span sub-, near-, and supercritical conditions. The outer to inner jet velocity ratio varies from ~1.2 to 23 and the momentum flux ratio varies from ~0.2 to 23. These ratios are mainly varied by changing the temperature and flow rates of the outer jet. At least 2000 backlit images were taken at 41kHz for each run. The main metric investigated is the length of the dark, or inner jet, core length. Both the axial length of the jet and the total, or curved, length are studied. A functional relation of the form A/MR^n describes the behavior of the axial length with the exponent being 0.2 (A:20-25) for subcritical conditions and 0.5 (A:5-12) for near and supercritical conditions. These results agree with historical data. The standard deviation of the axial length, which due to the large number of data points is within 0.03% of the RMS of the jet lengths fluctuations, also decreases with velocity ratio, for sub-, near-, and supercritical conditions. For momentum flux ratios ~O(1) the axial and total length differences between acoustics off and on are bigger than the error bars. For MR<~1 and MR>~5, the differences fall within the error bars. This preliminary result could imply that the dark core is in fact shortened by acoustics for MR~O(1).

NOMENCLATURE

A = constant
D = diameter with subscripts
H = gap between the injector exit plane and the thermocouple
HX = heat exchanger
L = axial dark core length
Lt = total or curved dark core length
MR = outer to inner jet momentum flux ratio
n = exponent for MR
R = radius with subscripts
T = temperature
VR = outer to inner jet velocity ratio

Subscripts
1, 2, 3, 4 = four diameters or radii of the coaxial injector from smallest to largest values
i = inner-jet
o = outer-jet
cr = critcal point

INTRODUCTION

There are two main motivations for this study. On the one hand, in the pursuit of higher specific impulse, the designs of liquid rocket engines (LRE's) are driven to higher chamber pressures. As the pressure increases the propellants go from subcritical to supercritical conditions. The Space Shuttle Main Engine (SSME) and the Vulcan engine for the Ariane 5 launch vehicles are examples of LRE's designed to operate above the critical pressures of each propellant individually. Our interest then is to understand the effects of transitioning from subcritical to supercritical pressure on an injector's jet characteristics such as mixing, atomization and breakup. We choose to study a coaxial injector since this design has proven effective for LRE's. In a typical coaxial injector for an LOX/LH2 engine, the oxygen is injected at subcritical temperatures in the center jet while the hydrogen is injected at supercritical temperatures, after being used as a coolant for the engine nozzle, in the coaxial jet. A typical velocity ratio between the outer and inner jets is about 10[1]. In this situation, as pointed out by previous researchers[1] the mixture no longer has a singular critical point but rather critical mixing lines that define its thermodynamic state. Therefore a phase-diagram becomes necessary when studying mixtures at supercritical pressures with respect to their individual propellants. Because of the added complexity introduced when working with mixtures, we choose to first use N2 as the sole working fluid.

The second motivation for the study is the problem that has been encountered since the late 1930's in LRE's, namely combustion instability[2.] Of the different types of instabilities, high frequency or acoustic instabilities are the most destructive to an engine. The damage can range from minor to catastrophic failure of an engine[3]. While a comprehensive understanding of what triggers these instabilities and how they evolve is still underway, a few things seem to be agreed upon. These instabilities are the result of coupling between the chamber acoustic modes and the injector fluid processes such as propellant injection, atomization, droplet vaporization, mixing and combustion heat release[4]. Of the different high-frequency acoustic modes, tangential modes (in the case of cylindrical chambers) seem to be the most damaging in rocket engines [5,6]. The equivalent of this mode is a transverse mode in a rectangular chamber. In the present study we have a coaxial jet with cryogenic N2 in a rectangular chamber. We excite this jet with a piezo-siren that produces high amplitude (max ~ 184 db) pressure oscillations and sets up a transverse acoustic field. We then study the effects of the acoustics on the jet by measuring the jet's dark core length and its standard deviation. By doing the experiments with cryogenic N2 we aim to study the sub-process of acoustics interaction with jet metrics such as dark core length (indicative of mixing efficiency) in isolation from the heat release created by the combustion process. In this sense, these cryogenic cold flow experiments at high pressure can be viewed as an intermediate step between atmospheric water cold flow experiments and fully reacting experiments.

Several series of experiments have previously been carried out at the present facility to study the effects of a transverse acoustic field on coaxial jets at sub-, near-, and supercritical conditions using N2[7,8]. In these studies, it was found that the jet's dark core length for an undisturbed jet decreases as the outer to inner momentum flux ratio (MR) and outer to inner velocity ratio (VR) increase. A good correlation was found between the dark core length and the MR. Two branches were found; one for two-phase conditions (at subcritical pressures) and another one for single-phase (at near- and supercritical pressures) conditions. The two-phase branch follows a correlation of the form $A/MR^{0.2}$ where A is a constant, and the single-phase branch follows a correlation of the form $A/MR^{0.5}$. These observations are in agreement with a wealth of historical data[7]. Furthermore, it was found that the dark core length standard deviation decreases at higher VR. This decrease, was suggested, could weaken a key feedback mechanism for the self-excitation process believed to play a fundamental role in LRE's combustion instability[7]. Most of the runs in that study consisted of 30 backlit images per run taken at 10 Hz. In the present study, we revisit most of the conditions run previously and expand the VR and MR in the subcritical regime. The new runs consist of at least 2000 backlit images taken at 41000 Hz. With the higher number of data points for each run, we aim to get statistically significant mean and standard deviations of the dark core length and compare the results with the previous trends. For example, with 2000 images, the standard deviation of the jet length is within 0.02% of the RMS of the jet length fluctuations, and they can be considered the same for all practical purposes. Also as part of this study we computed the total dark core length. That is, when the jet is excited by the acoustics, its shape changes

from mostly straight to curved. We compute the curved length to find out if the jet's length does decrease with acoustics, implying better mixing, or if it is only being curved.

EXPERIMENTAL SETUP

The facility used for this study is the Cryogenic Supercritical Laboratory (EC-4) at the Air Force Research Laboratory (AFRL) at Edwards Air Force Base, CA. An overview of the facility is shown in Figure 1. This facility has been extensively described in previous references [7, 8]. The gaseous N2 used to supply the inner and outer jets, and to pressurize the chambers, is obtained from the main supply line to the lab. The outer and inner jets are cooled by three separate counter-flow heat exchangers (HX's). The coolant is liquid nitrogen obtained from a cryogenic tank. One heat exchanger cools the inner jet and the other two cool the outer jet. The temperature (T) is controlled by adjusting the flow rate of liquid nitrogen through the HX's. The mass flow rate through the inner and outer jets is measured, before they are cooled, with Porter mass flow meters. This is because it was found that it is much easier to measure the flow rates for ambient temperature gases than for cryogenic fluids. The chamber pressure is measured with a Stellar 1500 transducer. To keep the amplitude of the acoustic oscillations to a maximum near the jet, an inner chamber was created (Figure 1). The inner chamber has nominal height of 2.6", width 3" and depth 0.5". Details for the injector used are shown in Figure 2. The diameter of the inner jet is 0.020". The outer jet has an inner diameter, D2 of 0.063" and outer diameter, D3 of 0.095". The length to inside diameter is 100 for the inner jet and 67 for the outer jet (taking as reference the mean width of the annular passage, or hydraulic diameter). There is a small bias of about 8% of the mean gap width. As can be seen from the same figure, the inner jet is recessed by 0.010" from the outer jet.

The temperature of the jets is measured with a type E thermocouple which has a bead diameter of 0.004". The accuracy of this thermocouple was checked with an RTD and found to be ±1.8F (1K). This thermocouple is traversed across the outer and inner jets to obtain a reading as close as possible to the injector exit plane. The radial profiles of the temperature were taken at intervals of 0.004" or 0.002" if the temperature varied significantly. The average distance from the exit plane, denoted H in Figure 2A is ~0.012".The density is computed from the measured flow rates, chamber pressure and jet temperature, using NIST's REFPROP[9]. From this, the VR and MR can be computed. Table 1 shows the range of test conditions used.

Chamber pressure, P (psia)	**Outer to inner jet Velocity ratio, VR**	**Outer to inner jet momentum flux ratio, MR**	**Range of inner jet temperature (F)**	**Nominal inner jet mass flow rate (lb/s) x10-6**	**Range of outer jet temperature (F)**
215	1.9-22.5	0.2-23.2	-262	617	-200 – -109
515	1.3-5.3	0.3-6.6	-235 to -227	637	-211 – -109
716	1.2-4.8	0.4-10.3	-222 to -211	648	-190 – -109

Table 1. Ranges of running conditions studies

The jet is visualized by taking backlit images using a Phantom 7.1 CMOS camera. The images have 128x256 pixels, and each pixel represents an area of about 0.003"x0.003". The framing rate was 41kHz. The exposure time varies from 7-9μs. The jet is backlit using a Newport variable power arc lamp set at 300W. The acoustic waves are generated using a piezo-siren custom-designed for AFRL by Hersh Acoustical Engineering, Inc. (Figure1). A piezo-ceramic element is externally excited with a sinusoidal wave at the desired driving frequency for the system. This frequency is chosen by manually varying the frequency on a signal generator until the highest amplitudes for the pressure waves are obtained. This signal is amplified and then fed to the piezo-siren. The movement of the piezo element is transmitted to the aluminum cone attached to it, and the cone then produces acoustics waves. To accommodate for the rectangular chamber a waveguide with a catenary contour is used to guide the waves from a circular cross-section to a rectangular cross-section (also shown in Figure 2). The sound pressure levels (SPL) in

the inner chamber range from 161 dB to 171 dB at for the first two resonance frequencies (~3.0 kHz and ~5.2 kHz). In this study only the first resonant frequency is studied.

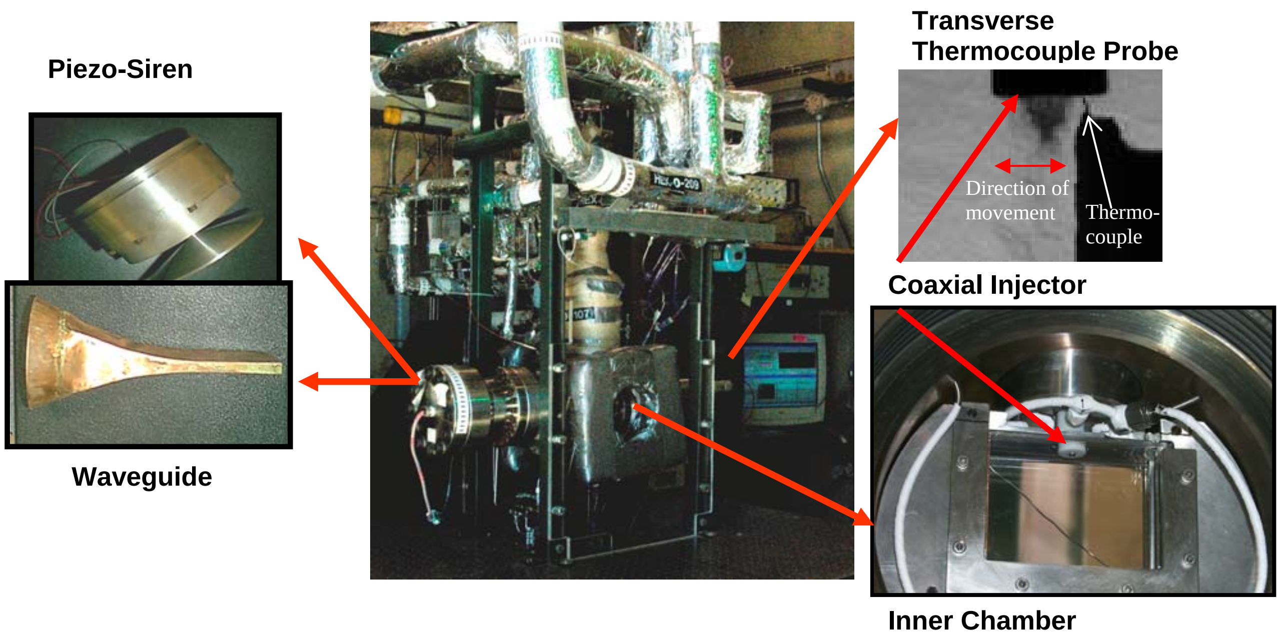


Figure 1. Overview of test facility used for this study, EC-4 at AFRL, Edwards.

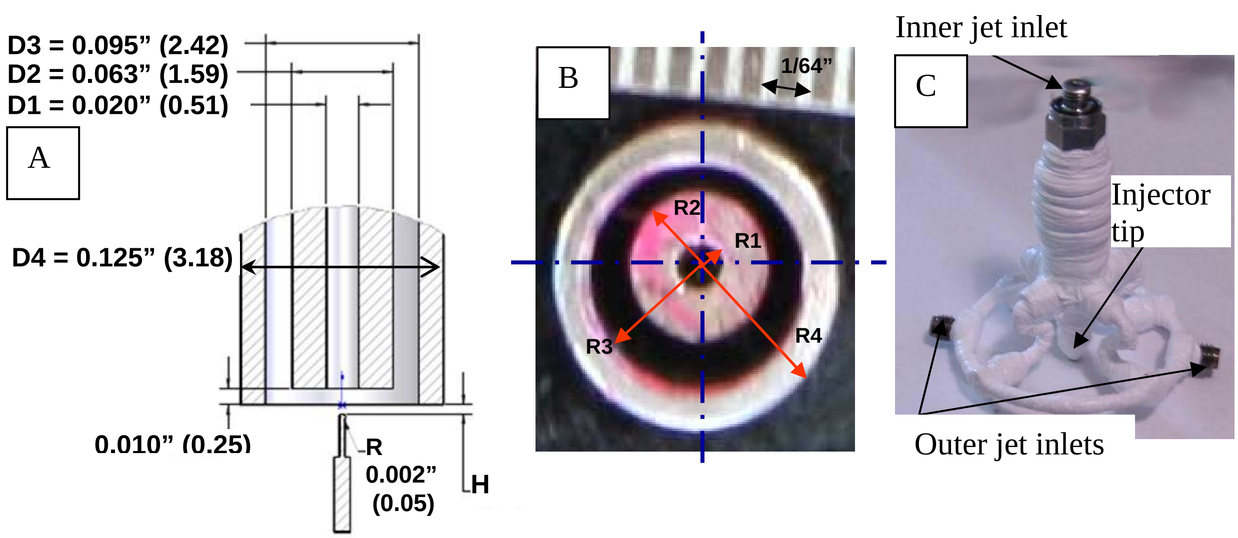


Figure 2. Injector Details. A: Schematic (dimension in parenthesis are in mm). B: Picture of coaxial injector tip. C: Injector overview.

RESULTS AND DISCUSSION

The main metric for this study is the dark core length. A typical image obtained is shown in Figure 3. In this case, Pchamber =217 psia, VR=7.50, MR=2.64 and the acoustic field is on. As you can see from the left picture, the inner jet, being colder and denser than the outer jet shows darker in the backlit image. It is the length of this denser core that is measured. There are many valid ways to define the dark core length. One only has to be cautious that the method chosen agrees with the intuitive length measured by the naked eye. In the present case, the images are first converted to a multi-page tiff format and then analyzed using Matlab. The raw image is converted, or thresholded, to a black and white image using

Matlab's subroutine "im2bw" (Figure 3B). The threshold level or pixel intensity value above which all pixels will be white and below which all pixels will be black, is determined using the matlab subroutine "graythresh". This subroutine uses Otsu's method[10] and it is based on the zeroth and first cumulative moments of the gray-level histrogram. Once a black and white (b&w) image is obtained, the length of the jet is finally determined by drawing a contour around the b&w image (using matlab subroutine "imcontour") and measuring the axial length of the longest contour attached to the injector as shown in Figure 3C. This length is an axial length, in the sense that it does not take into account any curviness of the jet, which is typically seen when the acoustic field is on. In an attempt to investigate whether the axial acoustic field does shorten the length of the jet or only curves it, the curved or total length was also measured. In this case, the same contour already used to measure the axial length is divided into a left and a right side (see Figure3D). The total length is defined as the average of the left and right side. The lengths given by the matlab subroutines were manually checked by selecting 50-60 images from each set of 2000 images and comparing the results with what the authors would select to be the length using the naked eye. Using these images the threshold level could be modified from the one automatically computed and then used to process the complete set of images.

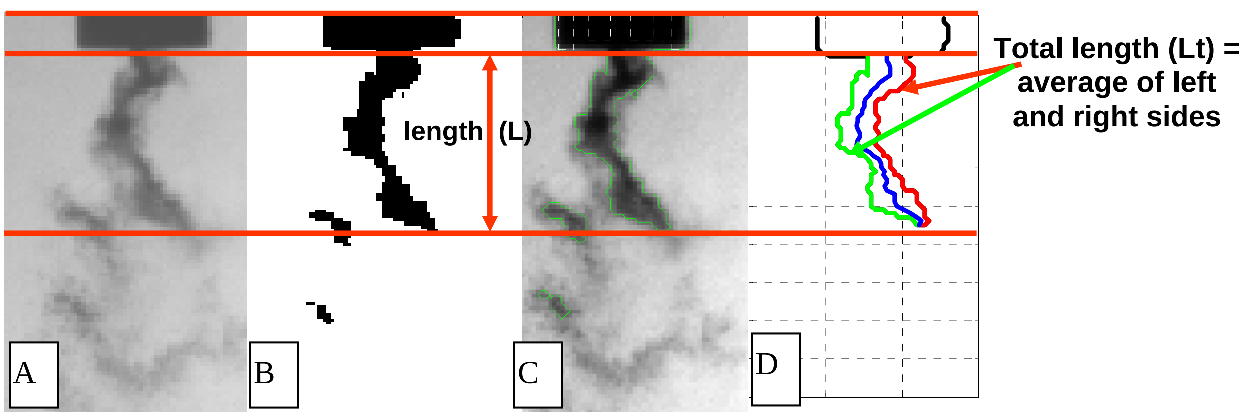


Figure 3 Measuring the dark core length. A: original image. B: Black and white image after thresholding. C: Contour used to define axial length (L). D: Schematic of how the total length is computed.

Three values for the chamber pressure are selected for the study to span subcritical to supercritical values: 215 (1.5), 515 (3.6), and 716 (4.9), psia (MPa). For reference, for N2, P_{cr}=493 psia (3.4 MPa), T_{cr}= -232.4 F (126.26 K). The temperature of the inner jet is nominally the saturation T, -261F, while for near and supercritical pressures T is kept as close as possible to the critical value. There are two ranges of operating T for the outer jet for each pressure value: a "high" range from about -153 to -100 F (170 to 200 K) and a "low" range of about -208 to -172 (140-160) F (K). In a previous study by Davis et a.l[7], two sets of outer jet T's were also chosen for each pressure. However, the dark core length seemed to be a function of the VR and MR and not of the outer jet T specifically. In this study, therefore, the emphasis was to sweep as large as possible a range of VR and MR even if the outer jet temperature was not constant. For subcritical pressure, the inner jet is liquid and the outer jet is a gas, so this is a two-phase system. For near and supercritical pressures, the inner jet is mostly above the T_{cr} and the outer jet is warmer still. Therefore, for those cases there is a one-phase system. As a verification of the low impact of the outer jet T, a sweep was made on VR at subcritical conditions with the outer jet T being -136 to -134 F (180-181K). These data points blended with the rest of the data points taken at outer jet T from -208 to -100 F as will be shown later. For the case of nearcritical pressure (515 psia) at the high outer T range, there are two cases of the inner jet T, one within 2 F (1 K) from T_{cr} (which is within the accuracy of the thermocouple, so the temperatures could span the critical point) and the other case with temperatures about 5 F (3 K) above the critical temperature. For the nearcritical pressure low T case, the inner jet is below T_{cr}. For supercritical pressures, the inner jet T is above T_{cr}.

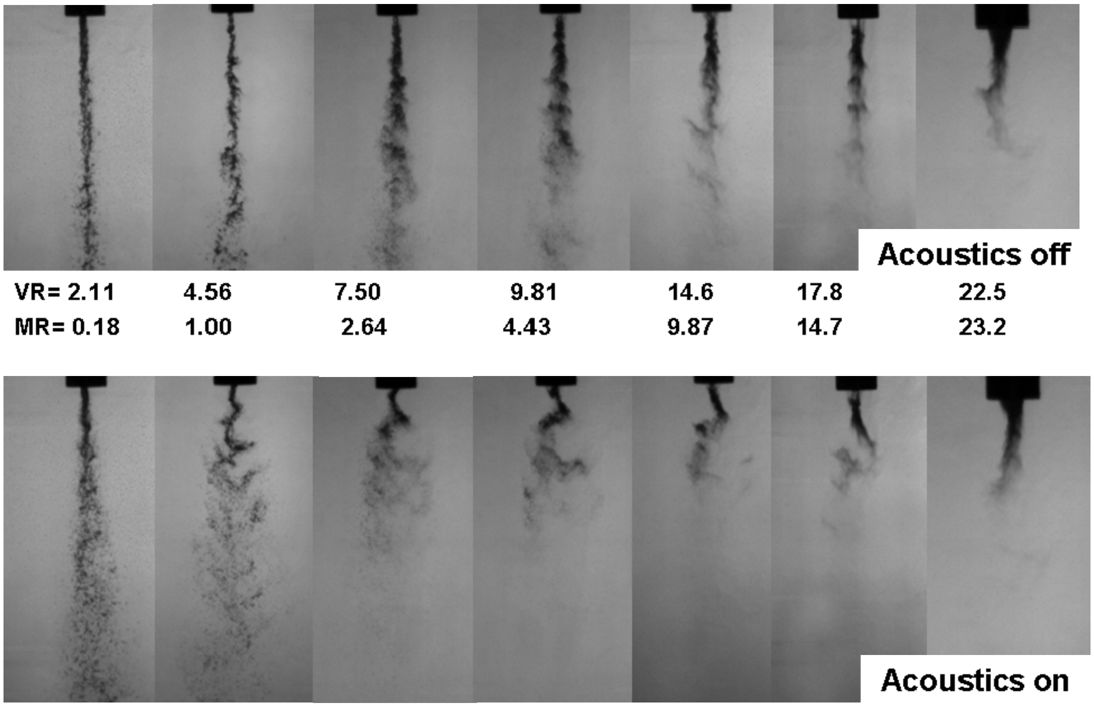


Figure 4. Collection of coaxial jet at subcritical pressure (~215 psia) with acoustics on and off for MR:0.18-23.2 and VR:2.11-22.5. The driving frequency is ~3kHz.

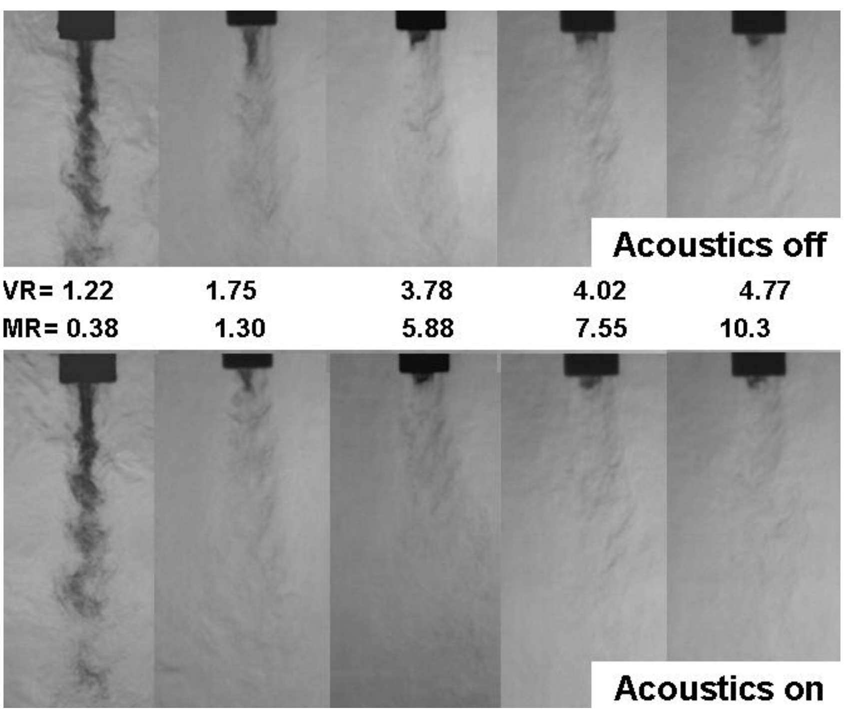


Figure 5. Collection of coaxial jet at supercritical pressure (~716psia) with acoustics on and off for MR:0.38-10.3 and VR:1.22-4.77. The driving frequency is ~3kHz.

A qualitative assessment of the coaxial jet at subcritical and supercritical conditions is shown in Figure 4Figure 5. The results for nearcritical pressures are not shown since they are very similar to those for the supercritical case. In these figures the top row represents the jet with no acoustics and the bottom row the jet with acoustics on (~3kHz). VR and MR increase from the left to the right images. A few features can be observed from these figures. The axial length decreases with VR and MR for both acoustics on and off confirming previous results[7]. However, observe that for low MR and VR values (left-most images for both figures) the impact of the acoustics on the jet, in terms of the number of bends of the jet, seems to be small. As MR and VR increase the jet curves more (more bends seen in the jet). However, for high values of MR and VR (MR>~10 for subcritical and MR>~6 for supercritical) the jet does not curve as much again. The reasons for this behavior are being further investigated. Note that at supercritical conditions the jet is shorter for a given value of MR or VR and by values of VR~4 and MR~6, the jet is very short and hardly any bends can be accommodated by the short jet.

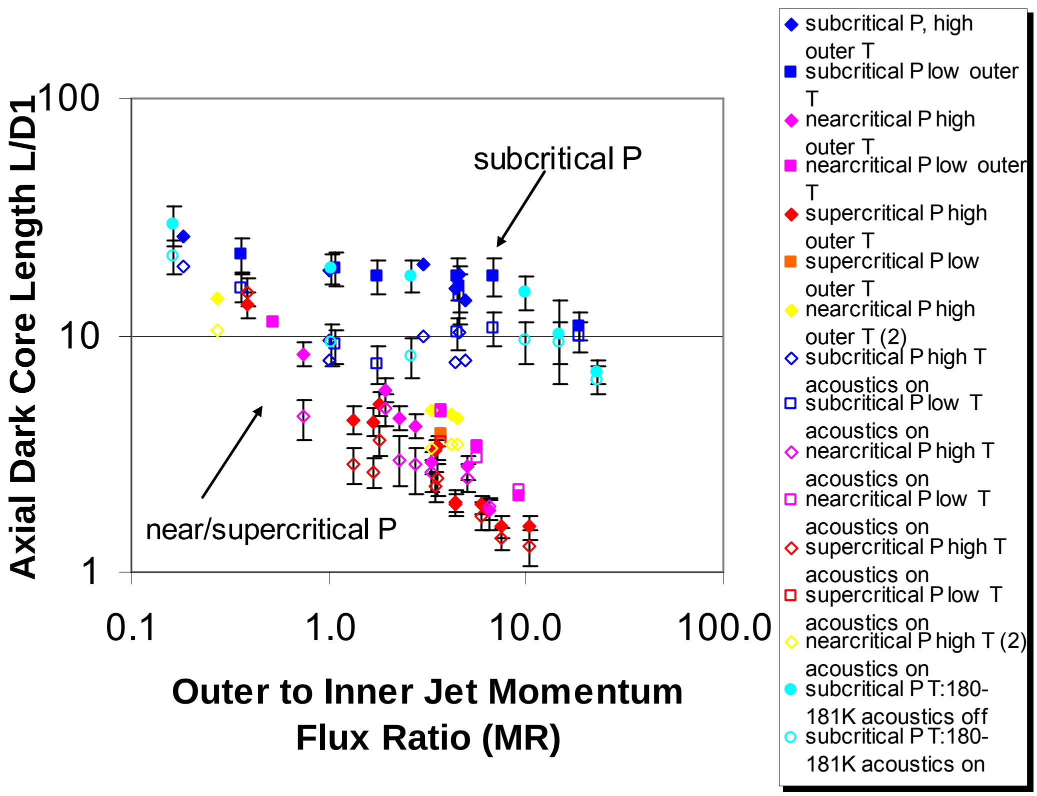


Figure 6. Axial Dark Core Length, L vs Outer to Inner Jet Momentum Flux Ratio (MR) for sub-, near-, and supercritical conditions with acoustics on and off.

Figure 6 shows the sub-, near-, and supercritical data with acoustics off (full symbols) and acoustics on (corresponding shallow symbol for a given full symbol). All the core length data presented here is normalized by the diameter of the inner jet, D1. The data called “Nearcritical P highT(2)” denotes the cases where the inner jet temperature was within 2F of the critical temperature. The dark core length for subcritical conditions (blue) is consistently higher than for the near- and supercritical conditions (red, pink, and yellow). The data for near- and supercritical conditions blends into one set of data consistent with previous results[7]. Note that for subcritical conditions, the entire set taken with outer jet temperatures ranging from -208 to -100 F (dark blue) blends with the data points taken at -136 to -134 F for the outer jet temperature (cyan), for both acoustics on and off. Therefore, for simplicity, in the next plots the data taken at 136 to -134 F will be included within the “subcritical P high T” data. Note that for all conditions the axial length of the jet gets shorter when the acoustics are on. For the few cases, where this is not the

case, the differences between the two lengths are within one pixel resolution. Finally, note that the percentage change between the length with acoustics off and on is largest for MR~O(1) for the subcritical case. The reason for this feature is being investigated.

Now let's focus on the axial length with acoustics off only and compare it with all the historical data compiled by Davis et al[11], including his own data (

Figure 7). The current data has error bars. It can be seen that the current data agrees well with past correlations. For the two-phase case (subcritical regime) the axial length has a functional relation with MR of the form $L \sim A/MR^n$ where n is 0.2 and A is a constant, in this case 20-25. Also the near and supercritical regimes are in a lower branch roughly bounded by $A/M^{0.5}$ where A :5-12.

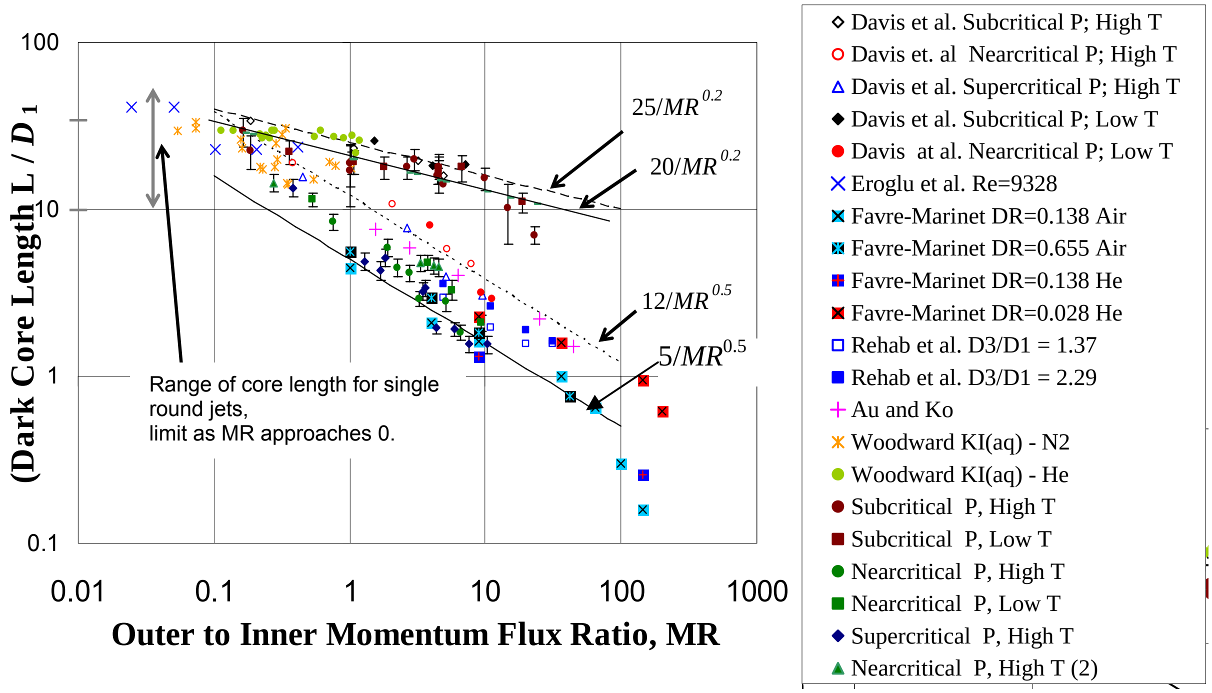
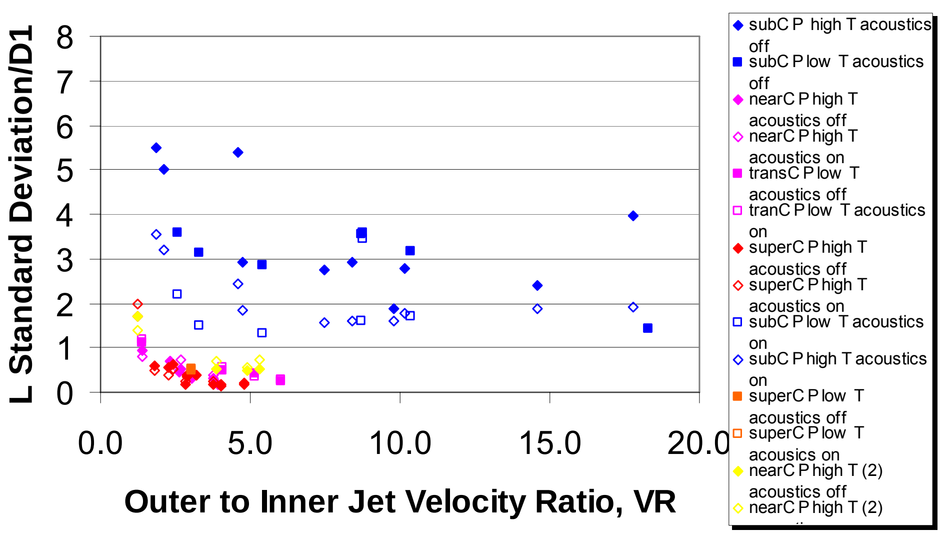


Figure 7. Comparison of data gathered in this study with historical data.



Distribution A

Figure 8. Standard deviation or RMS of dark core length fluctuations vs. outer to inner Velocity Ratio, VR

Having compared the axial dark core length of the jet with historical data and having found agreement, let's turn to the standard deviation. The results are shown in Figure 8. Again, there are two branches, one for subcritical and one for near and supercritical conditions. The standard deviation of the jet length for all conditions decreases as VR increases in agreement with previous results[7]. The faster decrease seems to happen for VR≤ ~5 which corresponds to MR≤ ~1. Then the standard deviation seems to plateau. Also for this case, the standard deviation decreases for both acoustics on and off. For the case of near and supercritical conditions, when the standard deviations/D1 gets smaller than 1, it is hard to make accurate statements about the differences between the cases with acoustics on and off because the pixel resolution is 0.2 D1.

The final metric to study is the total or curved length. The results, for acoustics on and off, are shown Figure 9. The same symbols and colors denote the same conditions as in Figure 6 for consistency. The results are consistent with those obtained for the axial length. Here too, the maximum percentage change of the length with and without acoustics is for MR~O(1). For this range the difference between the lengths with acoustics on and off are larger than the error bars. For lower (MR<~1) and higher (MR>~5) the differences between the jet length for acoustics on and off fall within the error bars. As expected, for a given condition the curved length is longer than the axial length. That the acoustics do shorten the dark core length for a certain range of MR, even when taking into account the waviness of the jet, has implications for the effects of acoustics on mixing. The shorter the dark core length is for a given condition, the faster the mixing occurred with the outer jet. Thus, acoustics seems to have an effect on mixing for MR~O(1).

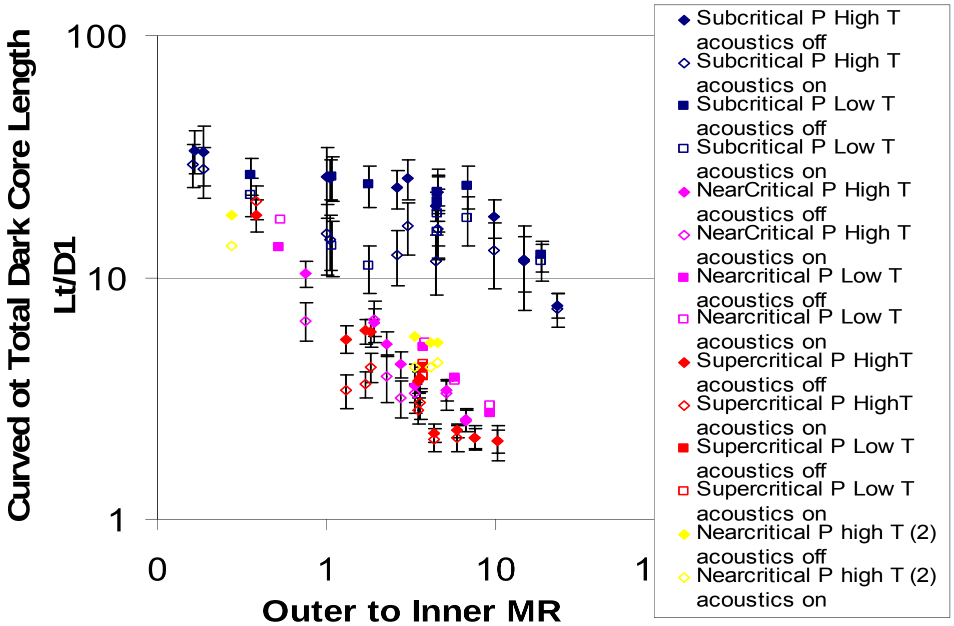


Figure 9. Curved or Total Dark Core Length Lt vs. Momentum Flux Ratio

CONCLUSIONS

An experimental study was completed to study the effects of chamber pressure, from subcritical to supercritical, outer to inner jet velocity ratio (VR) and outer to inner momentum flux ratio (MR) on a coaxial jet, which is either unexcited or under the influence of a transverse acoustic field at ~3kHz. The working fluid is cryogenic N2. For a given chamber pressure, the inner jet mass flow rate was kept nearly constant while the outer jet temperature and flow rate were varied to change VR and MR. The main metric to judge the effect of these variables on the jet was the dark core jet length, which is the length of the inner jet before its first break as it mixes with the outer jet. In this study, two lengths were defined, an axial length, L, and a curved or total length Lt. The choice of the latter definition arose from the fact that under most conditions, when the jet is excited by an acoustic field, the jet becomes curved and one wants to know if the acoustics shorten the dark core's length or only change its shape from more or less straight to curved. Each run consisted of at least 2000 backlit images taken at 41kHz. It was found that, consistent with previous results, the axial length decreases as VR and MR increase. A functional relation of the form A/MR^n describes the behavior of the axial length with the exponent being 0.2 (A:20-25) for subcritical conditions and 0.5 (A:5-12) for near and supercritical conditions. These trends agree with a wealth of historical data including previous data obtained in the same facility but with 30 frames per run at 10Hz. The standard deviation of the axial length, which due to the large number of data points is within 0.03% of RMS of the jet length fluctuations, also decreases with VR, for sub-, near-, and supercritical conditions. It is empirically well known that LRE's designed to operate at VR>~10 are more stable than those designed for lower VR's. The fact that the standard deviation of the axial length decrease with increasing VR can result on the jet being less affected by acoustic disturbances as VR increases. The curved or total length was found to decrease when acoustics were on for the cases studied. For MR~O(1) the curved length differences between acoustics off and on are bigger than the error bars. For MR<~1 and MR>~5, the differences fall within the error bars. This could imply that the dark core is in fact shortened by acoustics for MR~O(1). The reason for this behavior is being further investigated.

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